Renewable and Sustainable Energy Reviews 15 (2011) 3445–3453

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Life cycle assessment of sugar industry: A review

Manish Kumar Chauhan*, Varun, Sachin Chaudhary, Suneel Kumar, Samar

Department of Mechanical Engineering, National Institute of Technology, Hamirpur, H.P., India

A R T I C L E I N F O

Article history:
Received 9 February 2011
Accepted 7 April 2011

Keywords:
Life cycle assessment
Sugar industry
Cogeneration
Distillery
Waste management
Biomass

A B S T R A C T

Life cycle assessment (LCA) is a very important tool for the analysis of a process/system from its cradle to grave. This technique is very useful in the estimation of energy usage and environmental load by a product/system. The demand of sugar is very high in the world market. So sugar industry is the leading industry, which produces sugar with the help of sugarcane mostly. In sugar industry, different sizes of sugar crystals and also some by-products such as bagasse, molasses, filter cake and ash are produced. Out of these, some are used an input resource in other plants like power plant and distillery for optimal utilization of waste produced in sugar industry. The outputs of power plant (electricity and steam) used in mills, distilleries, residences of sugar industry and supply to grid for sell. The molasses is the waste of sugar which is used for the production of ethanol, so molasses is a by-product of sugar industry. LCA and waste management methods are very helpful to analyse and reduce the environmental effects.

Contents

1. Introduction

The industrial sector is playing a vital role in the world economy. Industry accounts for more than one-third of all the types of energy used in the world. Industries have a variety of highly energy-intensive systems, i.e. steam, process heating, and motor-driven equipments such as air compressor, pumps and fans in the industry. Industries have a lot of mobile and high power consumption parts which have several impacts on the environment. Thus electricity and energy demands are very high in the market. Most of the energy that industry utilizes is supplied from conventional electricity generation system (coal, oil, and gas) [1]. So the reduction of electricity consumption and impacts on the environment are very essential. There are different ways and techniques to solve these problems such as life cycle assessment (LCA) and optimization of industry. These techniques include maximization of output with same inputs, minimization of the cost used, reduction in material handling, and transportation, use of pollution control equipments,

* Corresponding author. Tel.: +91 988 254 4532.
E-mail address: manishku.25@gmail.com (M.K. Chauhan).

1364-0321/$ – see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.rser.2011.04.033

Nomenclature

As	arsenic
BOD_5	five-day biochemical oxygen demand
Cd	cadmium
CG	conventional gasoline
CH_4	methane
CO	carbon monoxide
COD	chemical oxygen demand
CO_2	carbon dioxide
Cu	copper
C_2H_5OH	ethanol
$C_{12}H_{22}O_{11}$	sucrose
EcL	eco-load
EIO	Economic Input–Output
E10	ethanol (a mixture of 10% ethanol and 90% gasoline)
Fe	iron
GHG	greenhouse gas
GJ	giga Joule
gm	gram
GWh	giga watt hour
ha	hectare
Hg	mercury
I–O	input output
ISO	international standard organization
kDa	kilo dalton
kg	kilogram
kW	kilo watt
kWh	kilo watt hour
L	liter
LCA	life cycle assessment
LHV	lower heating value
m^3	cubic meter
MJ	mega Joule
MoE	molasses-based ethanol
mt	million tonnes
MW	mega watts
MWCO	molecular weight cut-off
MWh	mega watt hour
na	not available
NETS	numerical environment total standard
NEV	net energy value
NH_3	ammonia
NMVOC	non-methane volatile organic compounds
NO_x	nitrogen oxide
NO_3^-	nitrate
N_2	nitrogen
N_2O	nitrous oxide
P	phosphorous
Pb	lead
PCA	Process Chain Analysis
PES	polyethersulphone
PM_{10}	particulate matter $\leq$10 μm in size
POCP	photochemical ozone creation potential
PO_4^{3-}	phosphates
REPA	resource and environmental profile analysis
SETAC	society of environmental toxicology and chemistry
SO_2	sulphur dioxide
SO_x	sulphur oxide
TSP	total suspended particles
TSS	total soluble salts
UASB	upflow anaerobic sludge blanket
UF	ultrafiltration
USA	United States of America
USDA	United states department of agriculture
VOC	volatile organic carbons
Zn	zinc

Table 1
Sugar production and consumption of the world during season 2000–01 to 2009–10 (in million tonnes) [1].

S. No.	Years	Sugar production	Sugar consumption
1	2009/10	160.503	164.339
2	2008/09	158.500	162.200
3	2007/08	167.600	158.400
4	2006/07	166.100	154.000
5	2005/06	146.252	142.711
6	2004/05	142.066	140.639
7	2003/04	141.955	140.191
8	2002/03	148.807	137.976
9	2001/02	134.566	134.545
10	2000/01	130.632	129.895

reduction in the emissions in environment and waste utilization. Amount of emission is not important but how much volume of air and water required diluting emission is important. Re-use is better than recycling, which is better than single use [2].

Life cycle assessment (LCA) and energy management are very essential tools to improve the overall efficiency of the industries [3]. Life cycle assessment is an important and comprehensive method for the analysis of environmental impact of products and services. Life cycle management is the managerial practices and organizational arrangements that apply to manage the entire life cycle of a product from its conception to finally its disposal. Energy management of the industry is a way of effective energy utilization to minimize its cost [4]. An efficient optimization of the system can result in significant energy and cost savings and also reduced CO_2 emissions. Understanding of energy utilization and waste energy can help to identify areas of energy intensity which leads to improve efficiency. Sugar industry is one of the leading industries of India. Sugar industry is entirely based on the availability of sugarcanes. That is why sugar industries are situated only in the cane growing areas and normally within the 25 km distance from sugarcane farms.

Sugarcane is the conversion form of solar energy into the chemical energy [5]. Sugarcane is tall grass with big stems which is largely grown in tropical countries [6]. In 2009–10, 1683 million metric tonne sugarcane was produced worldwide which amounts to 22.4% (weight) of the total world agricultural production. Sugar production and consumption of the world from season 2000–01 to 2009–10 are shown in Table 1. In the world, Brazil and India are holding first and second rank in sugarcane production countries, respectively. Though, each produces 275 million tonnes of sugarcane [7,8]. India is the second largest producer of sugar in the world. Indian mills produce 12 million tonnes of sugar annually over 430 sugar mills [9].

Sugar is one of the most important substrates for human diet. The top five nations, viz., India, Brazil, Thailand, Australia, and China accounted for nearly 40% of the total sugar production in the world. Sugar is produced approximately in 115 countries in the world. Out of these, 67 countries produce sugar from sugarcane, 39 from sugar beets and 9 countries from sugarcane as well as sugar beets [10]. In other words, sugar is produced 70% from sugarcane and 30% from sugar beet and cassava, etc. [6]. The production of sugar in different countries from season 2003–04 to 2009–10 is shown in Table 2.

Sugarcane is required to meet the basic demand of human body. So it is an essential product of the human life. Sugarcane is also a

Table 2
Country wise sugar production during season 2003–04 to 2009–10 (in million tonnes) [1].

S. No.	Name of country	2003–04	2004–05	2005–06	2006–07	2007–08	2008–09	2009–10
1	Brazil	26.400	28.370	29.500	32.635	33.582	39.656	36.400
2	India	15.450	13.590	18.340	30.766	28.800	16.100	19.460
3	China	10.730	11.240	10.910	13.041	16.131	13.512	11.566
4	Thailand	6.900	6.800	4.500	7.007	8.075	7.472	6.940
5	U.S.A.	7.843	7.718	7.385	7.661	7.472	6.778	7.118
6	Mexico	5.330	5.690	5.623	5.547	5.757	5.169	4.900
7	Pakistan	4.047	3.662	4.250	3.826	5.217	3.467	3.420
8	Australia	4.994	5.500	5.324	5.042	4.963	4.678	4.700
9	Germany	na	na	na	3.895	4.163	3.828	4.110
10	France	na	na	na	3.814	3.863	3.624	na
11	Russia	1.930	2.000	2.100	3.529	3.369	3.802	3.500
12	Indonesia	1.730	1.950	1.800	2.627	2.876	3.062	1.910
13	Philippines	2.160	2.160	2.100	2.324	2.417	2.095	2.000
14	Argentina	1.925	1.740	2.050	2.279	2.377	2.215	2.230
15	Colombia	2.635	2.645	2.420	2.343	2.266	2.241	2.200
16	South Africa	2.560	2.371	2.495	2.372	2.231	2.322	2.254
17	Guatemala	2.005	1.805	2.000	2.280	2.175	2.220	2.415
18	Poland	2.194	0	0	1.883	2.073	1.418	na
19	Turkey	1.915	1.990	2.175	1.989	2.049	2.338	2.260
20	Ukraine	1.580	1.400	1.750	2.712	1.998	1.658	1.380
21	Egypt	na	na	na	1.910	1.824	1.793	1.820
22	Cuba	2.300	2.000	1.600	1.181	1.480	1.300	1.000
23	United Kingdom	na	na	na	1.258	1.141	1.174	na
24	Iran	na	na	na	1.368	1.144	0.583	na

valuable crop for bio-products because it produces sugar which has very high demand in the market and also bagasse which provides energy in the form of fuel for the generation of electricity and steam [11]. Bagasse is used as input resource in 80 sugarcane producing countries [12]. In the past, sugar industry produced only sugar but nowadays sugar industries are involved in the production of sugar, electricity and ethanol. So sugar industry is now called as the cane industry [5].

2. Life cycle assessment

Life cycle assessment (LCA) is a powerful tool to analyse the interactions between human activities and environment [13]. It is also a technique for assessing several aspects which is related with the development of a product. It also acts as a tool for evaluating potential impact throughout a product's life (cradle to grave) from raw material acquisition, processing, manufacturing, use and finally its disposal [14,15]. It is also used for the comparison among several alternatives. Generally, systematic and adequate analysis of LCA depends upon the environmental aspects of products/systems. The principles of LCA are life cycle perspective, environmental focus, relative approach and functional unit, iterative approach, transparency, comprehensiveness and priority of scientific approach. The goal, scope, assumptions, description of data quality, methodologies and output of LCA analysis should be transparent [15,16]. LCA of any product includes four steps which are definition of goal and scope, inventory analysis, impact assessment and interpretation of results as shown in Fig. 1. The detailed methodology has been explained in the ISO standards [14,17–21].

LCA is a process for evaluating the environmental effects associated with a product, process or service over the course of its entire life cycle. Before LCA was known as LCA, it was under many names such as ecobalances, resource and environmental profile analysis (REPA), integral environmental analysis, and environmental profiles. It had been started a long way since the 1960s where its roots took shape as the result of the need for energy optimization within industry. The first "multi-criteria" study was carried out by Coca-Cola around 1969. The process was further developed at a SETAC conference in Vermont in 1990, which included inventory, interpretation and improvement. At a conference in 1991 a decision was actually made that the name of this concept should be life cycle assessment [2].

Net energy analysis is an important application of Life cycle assessment (LCA). The amount of remaining energy for the consumer use after the energy costs of finding, producing, upgrading and delivering have been paid is called net energy. Net energy measures the true value of an energy source to society [22,23]. Kato et al. [24] introduced a NETS (Numerical Environment Total Standard) method to analyse the environmental impact which gives numerical impact value. NETS value is defined as maximum sufferable value for human race. From the LCA point of view, NETS method is applied for eco-management and it gives accurate numerical values of environmental load. The total eco-load (EcL) value on environment is very important factor in the industrial process from cradle to grave. EcL is the summation of environmental load factor like fossil fuel depletion as input resources and global warming due to CO_2 emission as output. The value of EcL should be minimum for the purpose of optimization. NETS method is an attractive and powerful tool to calculate the LCA environmental loads of any industrial process or activity.

2.1. Types

There are two primary approaches for LCA. These are given below:

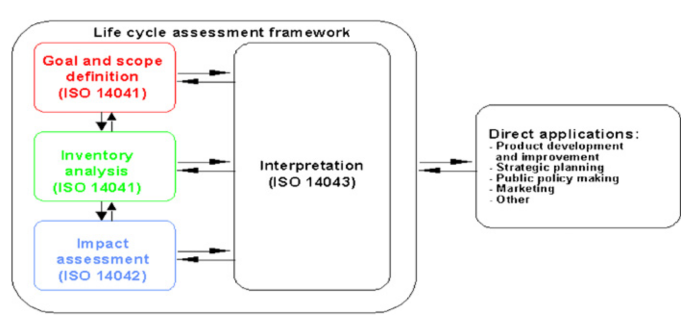

Fig. 1. Life cycle assessment framework.

1. Process Chain Analysis (PCA)
2. Economic Input–Output (EIO) model.

Process Chain Analysis LCA (also called Process LCA) begins with the identification of one particular product as the object of study. This product may be either in the form of a good or a service. After it is examined as to what resources were required directly/indirectly to produce this product. When the list of such inputs is obtained, the list is used to evaluate the total energy requirement and environmental emissions from this particular product. Performing a process analysis requires extensive data on the production processes of the product, which were selected for study [25].

An alternative approach to Process LCA (i.e. an LCA based on process modeling) is input–output (I–O) LCA. Input–output analysis was developed by Wassily Leontief who won the Nobel Prize in 1973. With I–O modeling, the product system that consists of supply chains is modeled using economic flow databases (input–output tables). These databases are collected and supplied by the statistical agencies of governments which describe the amount that each industrial sector spends on the goods and services produced by other sectors. Emissions and associated impacts are then assigned to different sectors [25]. On the basis of Japan's IO table, Nansai [26] has developed database on embodied energy use and the emission of air pollutants. In EIO analysis, with the help of price distortion effect on results can be eliminated and analysis can be made quite handy. Use of EIO analysis has some advantages and disadvantages. Advantages are improvement in data accuracy, easier to data handling, excellent use of policy application and disadvantages are drop in the accuracy of data and possibility of dispute over in the validity of applied price. I–O modeling provides greater comprehensiveness [27].

3. Sugar producing materials

Sugar is an essential product for human consumption. Sugar is mainly produced from sugarcane which is mostly grown in tropical regions of the world. Sugars are a major form of carbohydrates and are found probably in all green plants, they are also found in significant amounts in most fruits and vegetables. There are three main simple sugars namely sucrose, fructose and glucose. Sucrose is in fact a combination of fructose and glucose and the body quickly breaks down into these separate substances.

Sugar is generally produced by sugarcane, corn, sugar beet and cassava, etc. But in most of the countries, sugarcane is used in the production of sugar because several aspects are considered as overall cost, environmental effects, rate of sugar production and percentage of sucrose present in different materials. Sugar produces chiefly three types of juices [11]:

1. Sugarcane juice produces after milling of sugarcane and clarification (93% purity).
2. Sugar beet juice produces after diffusion of sugar beet and purification (92% purity).
3. Hydrolysate solution of corn produces after saccharification (hydrolysis) and filtration (95% purity).

Sugar consists of these contents such as arsenic (As), mercury (Hg), lead (Pb), cadmium (Cd), iron (Fe), copper (Cu) and zinc (Zn). But As, Hg, Cd, Pb contents are toxic elements in sugar solution. So these toxic contents should be removed from sugar solution with the help of purification and filtration processes. For improving the quality of white sugar, the contents of water-insoluble iron and water-soluble zinc decrease [28]. Renouf [11] compared sugarcane with corn and sugar beet and concluded that sugarcane has several advantages over other fossil-energy input, emission of greenhouse gases (GHGs) and acidification because milling of sugarcane produces bagasse which is a renewable energy source. But sugarcane has higher impact in water consumptions and eutrophication.

Crops follow these three favourable factors for the environment [11]:

1. Provide high crop yields.
2. Use nitrogen efficiency with minimum loss to the environment.
3. Produce more co-products.

In Thailand, there are three materials such as cassava, molasses and sugarcane used for the production of ethanol. But several studies have done on bio-ethanol in which ethanol is produced from grains such as corn, and wheat [29–32]. Renewable energy in India from MoE conversion is 21.2 MJ/L and in Thailand is 10.18 MJ/L with zero fossil energy input [33].

4. Sugar industry

In earlier time, generally sugar industry produced sugar only but nowadays sugar industry has become a combination of sugar mill, power plant and distillery, etc. which produce sugar, electricity and ethanol respectively. So, general layout of sugar industry is shown in Fig. 2.

4.1. Sugar mill processes

In sugar mill, sugar is produced through several processes which are given below [34].

4.1.1. Sugar milling

Initially, sugarcane is washed to remove excessive quantity of soil, rocks and trash. After washing and fibrising of sugarcane, then it passes through several types of mill which are connected in series and extracts raw juice and bagasse. Both products are separated in different places. Bagasse moves to co-generation plant for the production of electricity and raw juice moves for juice clarification and juice treatment.

4.1.2. Juice clarification and treatment

Raw juice has some non-sugar impurities are which removed with the help of mixture of some chemical reactants such as sulphur, and lime. Heating of juice is compulsory for chemical reactions. Chemical reactions separate raw juice in two parts. One is in liquid form and other one is in solid form. The liquid form is called syrup and solid form is called mud or filter cake. The juice is separated by clarifier which is separated as syrup and mud.

4.1.3. Crystallization

After treatment of juice, clarified juice or syrup is heated with the help of steam which produces from bagasse, to reduce the water contents in the syrup and converts into crystal form. In this process, sucrose contents will increase due to reduction of water contents in the syrup.

4.1.4. Centrifugal separation

After crystallization, syrup is passed through centrifugal tanks (Pans). These pans are used to separate sugar and molasses. Molasses supplied to distillery for ethanol production and sugar dried in driers. After drying, sugar is passed through graders which separate sugar into three categories: small (S), medium (M), and large (L).

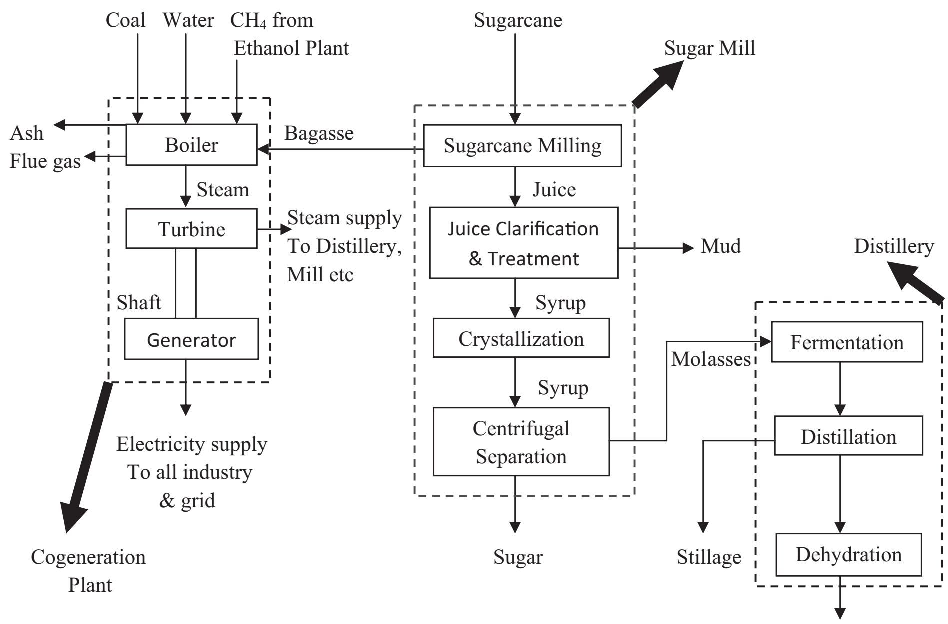

Fig. 2. General layout of the sugar industry.

5. LCA of sugar industry

The traditional sugar industry faces various problems from the wastes which contain organic materials because chemicals are to use for liming, sulphitation and phosphatation of raw juice treatment and removal for color. In sugar industry, the traditional methods have not been used to remove substances like waxes, starch, dextran, bacteria and sucrose. So the ultrafiltration process is used to take pure juice and lower color. Polyethersulphone (PES) membranes (5–100 kDa MWCO) and mineral Carbosep membranes (15–50 kDa MWCO) are used to reduce color and obtain an economically interesting permeate flux for MWCO between 30 and 50 kDa. Thus UF process partially reduces the pollution problem of sugar industry [35].

System dynamics has been developed by Forrester [36] at the Massachusetts Institute of Technology (MIT) in Cambridge. It is a method that analyses the behavior of complex feedback systems such as sugar industry in the field of economics, environmental science, corporate management, and technology. In sugar industry, co-generation system is considered for system dynamics modeling by which optimum energy output can be obtained [9]. For the assessment of the impacts of pollution charges, Wu and Chang [37] give a genetic-algorithm-based grey mathematical programming technique which gives various environmental cost impacts.

With the help of exergy analysis, several authors studied the improvements on sugarcane industry energy balance. They described different suggestions related to sugar industry in their analysis such as the increase of the number of evaporator effects, minimization of the quantity of water used in the industry, use of steam for juice heating, generation of surplus electricity from bagasse, necessity of thermal integration of the industry which has done by using vapour bleeding, juice heating with condensates, and evaporation with falling film evaporator [38–43].

Electricity production is an important source of revenue in sugar industry. For optimization of sugarcane industry, various factors help in the surplus electricity production such as bagasse % of cane, fiber % of cane, moisture % of bagasse, boiler efficiency, process steam consumption and electricity consumption in mill [44]. For dry bagasse, LHV (lower heating value) is 16 MJ/kg and for dry ligneous residue, LHV is 18 MJ/kg [45]. The gross calorific value of bagasse is 19250 kJ/kg at zero moisture and 9950 kJ/kg at 48% moisture. The net calorific value of bagasse is 8000 kJ/kg at 48% moisture [5,46,47]. In India, mostly sugar mills produce bagasse with 50% moisture content and density of 150 kg/m^3. 1 kg bagasse produces 2.2 kg of steam [44].

Generally electricity producing plants are multi-fuel input plants in which several fuels are used in mixed form. Fuel mix must be in proper ratio so that concentration of pollutants is reduced. To remove the effects on the environment and pollutant concentration, Jafar [48] applied fuel diversification strategy. The four fuel diversification strategy was developed in 1981 which is the extension of the 1979 National energy policy and the five fuel diversification strategy was developed in 1999.

In cogeneration power plant, generally live steam found at 22 bar and 300 °C but now live steam finds at 60 bar to fulfill plant energy requirement and produce surplus electricity [49]. Boiler is used in the production of steam and electricity with the help of bagasse and other fuels. To improve the efficiency of cogeneration plant, several methods are used such as the use of energy efficient pumps, motors and heat recovery equipments such as air pre-heater and economizer [50,51].

For electricity generation in sugar industry, the basic fuels are oil, coal, gas, hydropower, bagasse, and rice husk. But several by-products emit in the form of CO_2, SO_2 and NO_x by using coal, oil, rice husk and bagasse as a fuel. If pollution contents are high, these emitted by products are very harmful for human health, animals, crops and environment. Due to high concentration of pollutants, greenhouse and global warming effects are produced [48,52].

Allocation is an important part of LCA. In sugar industry, there are multiple outputs such as sugar, molasses and bagasse in which allocation is necessary. But allocation of bagasse is not to be considered because most of bagasse used in sugar industry itself for steam and electricity production. So two output sugar and molasses are only allocated and allocation varies according to price of sugar and molasses. In Thailand, allocation ratio of sugar and molasses was 8.6:1 in 2006 and after that it changed to 13.5:1 due to drop in molasses price [53].

Often, high quality of coal generates particulate emissions and solid waste. Due to oil as a burning fuel, sulphur gas emits into air so it leads to air pollution. Bagasse and rice husk are also produc-

Table 3
Results of LCA study on sugar industry.

S. No.	Author name/country	Results	
		Requirements/inputs	Emissions/outputs
1.	Richard Van Den Broek et al./Nicaragua	For 1 kWh electricity generation (A) Off-seasonal-eucalyptus 0.26 MJ fossil fuel use (B) Season-bagasse 0.020 MJ fossil fuel use	For 1 kWh electricity generation (A) Fuel oil produces 12 gm GHG emissions, gm acidification emissions (B) Biomass produces 778 gm GHG emissions, 25 gm acidification emissions.
2.	Toolseeram Ramjeawon/Mauritius	For 1 tonne of sugar production (A) 0.12 ha land (B) 553 m^3 water (C) 14235 MJ energy In milling of 1 tonne of sugarcane (A) 22.5 kWh electricity (B) 500 kg steam	For 1 tonne of sugar production (A) Emissions in air 160 kg CO_2 from fossil fuel, 1.7 kg TSP, 1.26 kg NO_x, 1.26 kg CO, 1.21 kg SO_2, 0.26 kg N_2O, 0.065 kg VOC, 0.002 kg CH_4 (B) Emissions in water 19.1 kg COD, 13.1 kg TSS, 6.3 kg BOD_5, 1.7 kg N_2, 0.37 kg $PO_4{}^{3-}$, 0.1 kg oil and grease, 0.002 kg herbicides (C) By-products 0.27 kg molasses. In milling of 1 tonne of sugarcane 0.3 tonnes bagasse, 65 kWh electricity
3.	M. A. Renouf et al./Australia	For 1 tonne of mono-saccharide production (A) 7 tonnes sugarcane (B) 70 MJ coal energy (C) 3.5 kg lime (CaO) (D) 0.28 kg phosphoric acid	In 1 ha land of sugarcane (A) Emissions in air 28.4 kg NO_x, 17 kg N_2O, 4.5 kg NH_3 (B) Emissions in water 46.8 kg NO_3, 2.4 kg P, 37.8 gm pesticide (C) By-products 85 tonnes sugarcane, 12.1 tonnes sugar For 1 tonne of monosaccharide production (A) Emissions in air 1487 gm NO_x, 827 gm PM_{10}, 621 gm SO_x, 174 gm CH_4, 77 gm N_2O, 1.7 gm NMVOC (B) Emissions in water 1.2 gm BOD_5, 1.8 gm suspended matter (C) Emissions in soil 365 kg filter cake/mill mud, 51 kg ash
4.	Thu Lan T. Nguyen et al./Thailand	For 1 tonne of sugarcane production (A) 0.017 ha land For 1 tonne of sugar production (B) 9.65 tonnes sugarcane	For milling of 1 tonne of sugarcane 103.6 kg sugar, 45.2 kg molasses, 247 kg bagasse, 16.94 kWh electricity In 1 ha land of sugarcane 57 tonnes sugarcane
5.	Ana M. Contreras et al./Cuba	For per day sugar production (A) 2300 tonnes sugarcane (B) 1.59 tonnes lime For per day sugarcane production (A) 48 ha land (B) 8743 kg diesel (C) 3115756.8 GJ solar energy	For per day sugar production (A) Emissions in air 4.24 tonnes PM_{10}, 0.374 tonnes NO_x (B) Emissions in water 10.46 tonnes COD, 0.12 tonnes P, 0.0805 tonnes N_2, 1.803 tonnes inorganic solids (C) Emissions in soil 69 tonnes filter cake, 2.69 tonnes ashes (D) By-products 216 tonnes sugar, 56 tonnes molasses For per day sugarcane production 2300 tonnes sugarcane, 483 tonnes agriculture wastes, 5.7 kg N_2O, 0.4 kg N_2 in water, 0.03 kg pesticides in soil, and 0.0015 kg pesticides in water
6.	Livison Mashoko et al./South Africa	For 1 tonne of sugar production (A) 846 tonnes sugarcane (B) 17000 m^3 of water (C) 0.15 ha of land (D) 71 kg of coal For milling of 1 tonne of sugarcane (A) 520 kg steam (B) 35 kWh electricity	For 1 tonne of sugar production (A) Emissions in air 7.5 kg CH_4, 196 kg CO_2, 0.5 kg N_2O, 2.18 kg SO_x, 7.5 kg NO_x (B) Emissions in water 6.6 kg BOD_7, 19 kg COD, 12 kg $NO_3{}^-$, 0.15 kg $PO_4{}^{3-}$, 0.05 kg suspended solids, 0.00126 kg Fe (C) Emissions in soil 368 kg ashes and slags, 0.03 kg hazardous waste (D) By-products 0.56 tonnes filter cake, 0.38 tonnes molasses, and 235.18 tonnes bagasse

ing CO_2 and ash but both are waste products of the industry, so the application of these in cogeneration plant helps to increase the efficiency of the plant [48]. Methane is the waste product of distillery but it is also used for electricity production in cogeneration plant. Combustion of 1 kg of methane produces 4.86 kWh electricity [54]. LCA study of sugar industry for different countries is shown in Table 3.

In sugar industry, several harmful contents emit in air and water. For 1 tonne of sugar production, 0.002 kg CH_4, 1.7 kg TSP (Total suspended particles), 1.21 kg SO_2, 1.26 kg NO_x, 1.26 kg CO and 160 kg

CO_2 from fossil fuel use are emitted into air and 1.7 kg N_2, 19.1 kg COD, 13.1 kg TSS (total soluble salts) are emitted into water in Mauritius sugar industry [55]. In Nicaragua sugar industries, when biomass is used in place of fuel oil, emission of CO_2 and SO_2 equivalent is 67 and 18 times lower [56].

In Malaysia, electricity generation is mostly fossil-based, in particular natural gas and oil. There are alternative fuels mixing policies which have different impacts on environment in electricity generation. Electricity sector of Malaysia changed in fuel use for electricity generation from 74.9% gas, 9.7% coal, 10.4% hydro and 5% petroleum in the year 2000 to 40% gas, 30% hydro, 29% coal and only 1% petroleum by the year 2020. According to input–output analysis, Al-Amin [52] suggests the result of emissions from electricity production in year 2020. The emission results are very high like CO_2 (800.52 mt), SO_2 (3.84 mt) and NO_x (18.32 mt) in comparison to year 2000 in Malaysia. These types of energy input–output (I–O) studies have been carried out in the studies of Casler and Hawdon [57,58].

Ethanol production emits the distillation residue which is called stillage or spent wash. This stillage is refined as biogas with the help of advanced anaerobic digestion system, e.g.: UASB (Upflow Anaerobic Sludge Blanket) reactors. By using open anaerobic system, there are two advantages energy (in the form of biogas) is secured and CH_4 emission to the atmosphere is avoided [59]. Ethanol conversion has several processes such as fermentation with yeast, distillation, dehydration, and produce residue mash (stillage) which can be used for the production of biogas from anaerobic digestion in UASB reactors and remaining stillage is stabilized in pond. So the NEV (net energy value) of MoE (molasses-based ethanol) and also renewable energy in India is more favourable than in Thailand [33].

6. LCA of by-products of sugar industry

Sugar industry produces several by-products such as bagasse and molasses which can be used as a resource for other plants. Bagasse is the resource for power plant and molasses is the resource for ethanol production plant. So bagasse and molasses are by-products of sugar mills and application of bagasse and molasses is the improvement of the environmental profile of the industry. These by-products of sugar industry help in the production of electricity, fuel, paper and organic chemicals [60,61]. The production of surplus electricity from biomass, bagasse and trash as a fuel, is very important for the reduction of process steam demand and the reduction of CO_2 emissions in order to prevent global warming [34].

In South African sugar industry, 1 tonne of raw sugar produced by 8.46 tonnes of sugarcane, 17000 m^3 of water, 0.15 ha of land and 71 kg of coal. But 0.56 tonnes of filter cake, 0.38 tonnes of molasses, 2.4 tonnes of bagasse which have 50% moisture contents and 368 kg of ashes and slugs are emitted. 1 tonne of sugar production required 23,800 MJ renewable and non-renewable energy in which 18,400 MJ of renewable energy is provided from bagasse. Consumption of fossil energy is very high in South African sugar industry rather than in the industries of Mauritius and Brazil [47].

In Mauritius sugar industry, 0.27 tonnes of molasses and 591 kWh of electricity from bagasse are produced during the production of 1 tonne sugar [55]. According to South Africa data, 1 kg sugar production produces by-products such as 0.3 kg of molasses and 1.25 kg of fibrous residue (dry basis), known as bagasse. 1 tonne of dry bagasse fed into acid hydrolysis process for production 186 kg ethanol [12]. According to Thailand data, 1 tonne sugarcane produces 103.6 kg sugar and 45.2 kg molasses [62].

6.1. Bagasse

Bagasse is a by-product for sugar industry but it is used as an input resource of power plants for the production of electricity. In Nicaragua, sugar mills generate electricity from bagasse and eucalyptus. Bagasse is mostly used during sugarcane season and eucalyptus during the rest of the year. Bagasse is a useful by-product for generating heat and power [56]. Generally by-product of sugar mill bagasse contains 50% fiber, 48% moisture and 2% sugar which is burnt to generate steam and electricity. Production of electricity from bagasse provides better environmental benefits rather than production of electricity from oil and coal [5].

Kiatkittipong [63] studied four alternatives of bagasse utilization which are given below:

1. Landfilling with the use of landfill gas.
2. Anaerobic decomposition in a reactor with biogas production.
3. Incineration for electricity production.
4. Pulp production.

In pulp production, bagasse is used as input resource for paper production. In landfilling, methane gas is produced for electricity generation. Bagasse is also directly used for power generation. Anaerobic decomposition process is also produced methane gas for electricity production but this process is taken place in well controlled reactor. So, anaerobic decomposition of bagasse occurs at faster rate than in the landfill and also gives the best environmental performance than other options. But incineration of bagasse for power generation was more favourable environmental process than other three of them except in the photochemical oxidant potential [63].

Ramjeawon [5] compared the data of 1 GWh electricity production from bagasse and coal. Bagasse-derived electricity represents well in categories of greenhouse gas emissions, acidification, non-renewable energy input, human toxicity and summer smog. But it represents poorly in categories of eutrophication and fresh-water consumption. These results are matched with the result given by Renouf (Thesis) [64].

6.2. Molasses

Molasses is also a by-product for sugar industry but it is used as an input resource of distillery in the production of ethanol. Analysis of ethanol is done either directly from sugarcane [65] or indirectly as by-product of sugar industry, molasses [8]. Yeast is used to convert sucrose ($C_{12}H_{22}O_{11}$) into ethanol (C_2H_5OH) and carbon dioxide (CO_2) with the help of fermentation process [13]. Ethanol has lower heating value (LHV) which is compensated by its higher combustion efficiency in comparison to conventional gasoline (CG) [65–67]. In Brazil, bio-ethanol is produced from sugarcane but now it is produced from both sugarcane and bagasse. Previously bagasse was used to generate heat and power generation but now it uses to produce ethanol. 30.1 kg of sugarcane is required for 1 kg of ethanol production but when bagasse and sugarcane both are used, 12.6 kg of sugarcane is required. But from LCA point of view, when GHG emissions are considered, the production of electricity from bagasse is better option than the production of ethanol from bagasse [68].

Contreras [6] has compared the life cycle assessment of four alternatives for using by-products of sugarcane production. First one is the conventional sugar production in which bagasse is used for steam and electricity generation. Second one is similar to the first one but waste water is used for irrigation and filter cake/ash are used as fertilizers. In third alternative, waste water and filter cake are used for biogas production. But sludge from this digester is used in fertilization. In the last alternative, molasses and biogas

are also used for the production of alcohol. In life cycle assessment of four alternatives, fourth one is best according to environment and economic conditions.

For the improvement of molasses based ethanol production, Nguyen [69] has given three considerations: substituting biomass, using cane trash for fuel and capturing CH_4 from distillery stillage (residue). Ethanol can be used as an engine fuel. In Brazil, the production of fuel ethanol depends mostly on a plantation system and burning of sugarcanes prior to harvesting. In LCA of ethanol production, environment is affected by nutrient application, burning in harvesting and use of diesel. Due to these acts, several pollutants have been emitted in the production of ethanol. To reduce environmental effects, several tasks have been considered such as avoiding use of nutrients, harvest sugarcane without burning and replace diesel to a renewable fuel as biodiesel from vegetable oils [13].

Various cars which are based on CG and E10 fuel have been tested in the PTT Research and Technology Institute, Thailand. One test has held on Toyota 1.6 L/2000. In this car, the average fuel consumption for 1 km car running on CG and E10 is 0.0742 and 0.0751 liter [70]. In comparison to molasses-based E10 and CG, E10 reduces fossil energy use, petroleum use, CO_2 and NO_x emission. But E10 produces air pollution due to emission of CH_4, N_2O, CO, SO_2, VOC and PM_{10} (particulate matter $\leq$10 μm in size) [53].

6.3. Wastes of sugar industry

Sugar industry has several waste products which can also be used for other purpose. Filter cake and boiler ash are waste products of sugar industry but these can be used to improve soil fertility in sugarcane fields. This is also an advantage of sugar production and an improvement of sugarcane production [11].

The tops, leaves and trash of sugarcane are by-products of sugarcane and waste product for sugar industry. These are used for producing meals that are an important nutrient source in animal diets and also used in mills to provide further biomass feedstock for processing [12,28]. Cane trash can also be used to improve energy input for ethanol production [33]. Open burning of cane trash emits several air pollutants such as CO and VOC (volatile organic carbons) which consider substantially to POCP (photochemical ozone creation potential) and also produce acidification, and eutrophication effects. So utilization of cane trash as a fuel is necessary in sugar industry [47,69].

7. Conclusions

A general tendency of results for sugar industry is clearly in the favour of optimal utilization of waste produced in sugar industry. Main resources of sugar industry are electricity. Sugar is mainly produced from sugarcane which is mostly grown in tropical region of the world. Bagasse and molasses are by-products of sugar industry but they are used as a resource in other plants. Bagasse is used in cogeneration plant for the production of electricity and steam which is used as an input resource in sugar mill, distillery, cogeneration plant, residences of plants and supply to grid for sell. In off season of sugar industry, electricity is produced from other resources such as coal, rice husk, and CH_4, etc. but in some countries, eucalyptus uses for electricity production. So multi-fuel boiler uses in cogeneration plant.

Molasses is also a by-product which is used in distillery for ethanol production. Distillery produces ethanol as a product and stillage as a waste product. In UASB reactor, anaerobic digestion of stillage produces biogas as a resource and CH_4 which is used in cogeneration plant for electricity production. Filter cake/ash is a waste of sugar industry which is used for fertilization of sugarcane field and some other fields of agriculture. The tops, leave and trash of sugarcane are also waste products of sugar industry. These are used in mills to provide biomass feedstock. Sugar industry requires some resources and produces some product, by-products and wastes. Sugar industry also emits some harmful gases and solid particles in air and water which directly affects the environment in terms global warming, acidification and eutrophication.

References

[1] United States Department of Agriculture Report. http://www.usda.gov/.
[2] Baumann H, Tillman AM. The Hitch Hiker's guide to LCA. Sweden: Studentlitteratur; 2004.
[3] Rajan CG. Optimization energy in industries. Tata McGraw-Hill; 2001.
[4] Capehart, Turner, Kennedy. Guide to energy management. Lilburn, Georgia: The Fairmont press Inc.; 1997.
[5] Ramjeawon T. Life cycle assessment of electricity generation from bagasse in Mauritius. Journal of Cleaner Production 2008;16:1727–34.
[6] Contreras AM, Elena Rosa, Maylier Pérez, Langenhove HV, Dewulf J. Comparative life cycle assessment of four alternatives for using by-products of cane sugar production. Journal of Cleaner Production 2009;17:772–9.
[7] Macedo I. Greenhouse gas emissions and energy balances in bio-ethanol production and utilization in Brazil. Biomass and Bioenergy 1998;14(1):77–81.
[8] Prakash R, Henham A, Bhat I. Net energy and gross pollution from bio-ethanol production in India. Fuel 1998;77(14):1629–33.
[9] Yarnal GS, Puranik VS. Energy management in cogeneration system of sugar industry using system dynamics modeling. Cogeneration & Distributed Generation Journal 2009;24(3):7–22.
[10] Lichts FO. International and sweetener report. International Sugar Journal 2007;139(12).
[11] Renouf MA, Wegener MK, Nielsen LK. An environmental life cycle assessment comparing Australian sugarcane with US corn and UK sugar beet as producers of sugars for fermentation. Biomass and Bioenergy 2008;32:1144–55.
[12] Botha T, Blottnitz HV. A comparison of the environmental benefits of bagasse-derived electricity and fuel ethanol on a life-cycle basis. Energy Policy 2006;34:2654–61.
[13] Ometto AR, Hauschild MZ, Roma WNL. Lifecycle assessment of fuel ethanol from sugarcane in Brazil. The International Journal of Life Cycle Assessment 2009;14:236–47.
[14] ISO 14040. Environmental management – life cycle assessment – principles and framework; 1997.
[15] Varun, Bhat IK, Prakash R. LCA of renewable energy for electricity generation systems – a review. Renewable and Sustainable Energy Reviews 2009;13:1067–73.
[16] Varun, Prakash R, Bhat IK. Energy, economic and environmental impacts of renewable energy systems. Renewable and Sustainable Energy Reviews 2009;13:2716–21.
[17] ISO 14041. Environmental management – life cycle assessment – goal and scope definition and inventory analysis; 1998.
[18] ISO 14042. Environmental management – life cycle assessment – life cycle impact assessment; 2000.
[19] ISO 14043. Environmental management – life cycle assessment – life cycle interpretation; 2000.
[20] ISO 14044. Environmental management – life cycle assessment – requirements and guidelines; 2006.
[21] Rebitzer G, Ekvall T, Frischknecht R, Hunkeler D, Norris G, Rydberg T, et al. Life Cycle Assessment. Part 1. Framework, goal and scope definition, inventory analysis and applications. Environment International 2004;30:701–20.
[22] Huettner DA. Net energy analysis: an economic assessment. Science 1976;192(4235):101–4.
[23] Varun, Prakash R, Bhat IK. A figure of merit for evaluating sustainability of renewable energy systems. Renewable and Sustainable Energy Reviews 2010;14:1640–3.
[24] Kato S, Maruyama N, Nikai Y, Takai H, Widiyanto A. Life cycle assessment estimation for eco-management of co-generation systems. Journal of Energy Resources Technology – Transactions of the (ASME) 2001;123:15–20.
[25] Varun, Prakash R, Bhat IK. Life cycle analysis of run-of river small hydro power plants in India. The Open Renewable Energy Journal 2008;1:11–6.
[26] Nansai K, Moriguchi Y, Tohno S. Embodied energy and emission intensity data for Japan USING IO tables (3EID). Center for Global environmental research (CGER) [CGER-D031-2002]; 2002.
[27] Chung WS, Tohno S, Shim SY. An estimation of energy and GHG emission intensity caused by energy consumption in Korea: an energy IO approach. Applied Energy 2009;86:1902–14.
[28] Wojtczak M, Krol B. Content of iron, copper and zinc in white sugar samples from Polish and other European sugar factories. Food Additives and Contaminants 2002;19(10):984–9.
[29] Wang M, Saricks C, Santini D. Effects of fuel ethanol use on fuel-cycle energy and greenhouse gas emissions. Argonne, IL: Center for Transportation Research, Argonne National Laboratory; 1999.
[30] Shapouri H, Duffield JA, McAloon A, Wang M. The 2001 net energy balance of corn ethanol. US Department of Agriculture; 2004.

[31] Kim S, Dale BE. Allocation procedure in ethanol production system from corn grain. I. System expansion. The International Journal of Life Cycle Assessment 2002;7(4):237–43.
[32] Natural Resources Canada. The addition of ethanol from wheat to GHGenius prepared by (S&T)^2 consultants inc.; 2003, http://www.gov.mb.ca/est/energy/ethanol/wheat-ethanolreport.pdf.
[33] Nguyen TLT, Shabbir H, Gheewala, Garivait S. Full chain energy analysis of fuel ethanol from cane molasses in Thailand. Applied Energy 2008;85:722–34.
[34] Ensinas AV, Nebra SA, Lozano MA, Serra LM. Analysis of process steam demand reduction and electricity generation in sugar and ethanol production from sugarcane. Energy Conversion and Management 2007;48:2978–87.
[35] Karode SK, Gupta BB, Courtois T. Ultrafiltration of raw Indian sugar solution using polymeric and mineral membranes. Separation Science and Technology 2000;35(15):2473–83.
[36] Forrester JW. The beginning of system dynamics. In: International meeting of the system dynamics society. 1989.
[37] Wu CC, Chang NB. Grey input–output analysis and its application for environmental cost allocating. European Journal of Operational Research 2003;145:175–201.
[38] Tekin T, Bayramoglu M. Exergy and structural analysis of raw juice production and steam-power units of a sugar production plant. Energy 2001;26:287–97.
[39] Bayrak M, Midilli A, Nurveren K. Energy and exergy analyses of sugar production stages. International Journal of Energy Research 2003;27:989–1001.
[40] Ram JR, Banerjee R. Energy and cogeneration targeting for a sugar factory. Applied Thermal Engineering 2003;23:1567–75.
[41] Upadhiaya UC. Cogeneration of steam and electric power. International Sugar Journal 1992;94:11–7.
[42] Ensinas AV, Nebra SA, Lozano MA, Serra LM. Optimization of thermal energy consumption in sugarcane factories. In: ECOS 2006, 19th international conference on efficiency, cost, optimization, simulation and environmental impact of energy systems. 2006. p. 569–76.
[43] Ensinas AV, Modesto M, Nebra SA, Serra L. Exergy loss minimization in sugarcane industries with integrated sugar, ethanol and electricity production. In: 4th Dubrovnik conference on sustainable development of energy, water and environment system. 2007.
[44] Javalagi CM, Patil HR, Bhushi UM. Statistical modeling of steam generation for cogeneration in Indian sugar industry: a case study. Cogeneration & Distributed Generation Journal 2010;25(1):18–34.
[45] Cuzens JC, Miller JR. Acid hydrolysis of bagasse for ethanol production. Renewable Energy 1997;102(3):285–90.
[46] Deepchand K. Bagasse energy cogeneration in Mauritius. In: Proceedings: AFREPREN regional policy seminar on cogeneration. 2000. p. 6–25.
[47] Mashoko L, Mbohwa C, Thomas VM. LCA of the South African sugar industry. Journal of Environmental Planning and Management 2010;53(6):793–807.
[48] Jafara AH, Al-Amin AQ, Siwar C. Environmental impact of alternative fuel mix in electricity generation in Malaysia. Renewable Energy 2008;33:2229–35.
[49] Macedo IC, Verde Leal MRL, Hassuani SJ. Sugarcane residues for power generation in the sugar/ethanol mills in Brazil. Energy for Sustainable Development 2001;5(1):77–82.
[50] Deepchand K. Commercial scale cogeneration of bagasse energy in Mauritius. Energy for Sustainable Development 2001;V(1).
[51] Ramjatun SS, Gukhool J, Seebaluck D. Optimization of power generation in the local cane factories, University of Mauritius, Réduit, Mauritius. Science and Technology-Research Journal 1999;3:79–85.
[52] Al-Amin AQ, Siwar C, Jaafar AH. Energy use and environment impact of new alternative fuel mix in electricity generation in Malaysia. The Open Renewable Energy Journal 2009;2:25–32.
[53] Nguyen TLT, Gheewala SH. Fuel ethanol from cane molasses in Thailand: environmental and cost performance. Energy Policy 2008;36:1589–99.
[54] Aye L, Widjaya ER. Environmental and economic analyses of waste disposal options for traditional markets in Indonesia. Waste Management 2006;26(10):1180–91.
[55] Ramjeawon T. Life cycle assessment of cane-sugar on the island of Mauritius. The International Journal of Life Cycle Assessment 2004;9(4):254–60.
[56] Broek RVD, Burg TVD, Wijk AV, Turenburg W. Electricity generation from eucalyptus and bagasse by sugar mills in Nicaragua. Biomass and Bioenergy 2000;19:311–35.
[57] Casler S, Wilbur S. Energy input–output analysis: a simple guide. Resource Energy 1984;6(2):187–201.
[58] Hawdon D, Pearson P. Input–output simulations of energy, environment, economy interactions in the UK. Energy Economics 1995;17:73–86.
[59] Nguyen TLT, Gheewala SH, Garivait S. Fossil energy savings and GHG mitigation potentials of ethanol as a gasoline substitute in Thailand. Energy Policy 2007;35(10):5195–205.
[60] Paturau JM. By-products of the cane sugar industry. An introduction to their industrial utilization. Amsterdam: Elsevier; 1989.
[61] Manohar Rao PJ. Industrial utilization of sugar cane and its by-products. New Delhi: ISPCK; 1997.
[62] Prasertsri P. Thailand sugar annual 2007, USDA foreign agriculture service – gain report – Global agriculture information network, gain report number: TH7048.
[63] Kiatkittipong W, Wongsuchoto P, Pavasant P. Life cycle assessment of bagasse waste management options. Waste Management 2009;29:1628–33.
[64] Renouf M. Life Cycle Assessment of electricity generation from bagasse. Honours Thesis, Department of Geographical Sciences and Planning, The University of Queensland; 2000.
[65] Macedo IC, Leal MRLV, Silva JEAR. Assessment of greenhouse gas emissions in the production and use of fuel ethanol in Brazil. Secretariat of the environment, Government of the state of São Paulo; 2004.
[66] Brekke K. American coalition for ethanol releases results of fuel economy study. American Coalition for Ethanol; 2005, http://www.ethanol.org/documents/ACEFuelEconomyStudy.pdf.
[67] Fu GZ, Chan AW, Minns DE. Life cycle assessment of bio-ethanol derived from cellulose. The International Journal of Life Cycle Assessment 2003;8(3):137–41.
[68] Lin Luo, Voet EVD, Huppes G. Life cycle assessment and life cycle costing of bioethanol from sugarcane in Brazil. Renewable and Sustainable Energy Reviews 2009;13:1613–9.
[69] Nguyen TLT, Gheewala SH. Life cycle assessment of fuel ethanol from cane molasses in Thailand. The International Journal of Life Cycle Assessment 2008;13:301–11.
[70] Tantithumpoosit W. History, roadmap and success of using ethanol blended gasoline in Thailand. In: Second Asian petroleum technology symposium program. 2004.